*International Journal of Engineering Science Invention (IJESI)*
*ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726*
*www.ijesi.org ||Volume 8 Issue 03 Series. III || March 2019 || PP 35-39*

# "Enhancement of heat transfer performance in solar air heaters : a review"

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***Abstract :-*** *Artificial roughness is applied on the absorber plate and is the most efficient method to improve thermal performance of solar air heaters. Experimental investigations with different roughness geometries show that the enhancement in heat transfer is accompanied by considerable rise in pumping power. Heat transfer enhancement techniques are divided into two groups : active and passive techniques. Providing an artificial roughness on a heat transferring surface is an effective passive heat transfer technique to enhance the rate of heat transfer . In this paper, reviews of various artificial roughness elements is used in order to improve thermo hydraulic performance of a solar air heaters .The objective of this paper is to review various studies, in which different artificial roughness elements are used to enhance the heat transfer rate with little penalty of friction. Correlations is developed for heat transfer and friction factor for solar air heater duct by taking different roughened surface geometries are given in tabular form. This paper also conclude that artificial roughness in the form of different types of ribs used in heat transferring system, increase heat transfer rate many times as compare to conventional type system.*

***Key Words :-*** *Solar air heater, artificial roughness, active and passive technique, friction factor.*

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Date of Submission: 25-02-2019 Date of acceptance: 18-03-2019

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## I. Introduction

Solar air heater is a device which is used to convert the solar energy into heat energy. in solar air heater, heat generated by solar energy is collected over a collector and then taken away by the fluid flowing (i.e. air) then used for various purposes and in many applications such as crop drying, space heating, timber seasoning, clay building components etc. Though the thermal efficiency of solar air heaters is very low. In order to make the solar air heater economically more viable, their thermal efficiency needs to be improved. This can be done by enhancing the heat transfer co-efficient between the absorber plate and air flow through a duct. In this paper an attempt has been made to review the reported roughness geometries used for creating artificial roughness to enhance the heat transfer rate . Artificial roughness is basically a passive heat transfer enhancement technique by which thermo hydraulic performance of a solar air heater can be improved.

The artificial roughness has been used extensively for the enhancement of forced convective heat transfer, which Further requires flow at the heat transferring surface to be turbulent. However energy for creating such turbulence has to come from the fan or blower and the excessive power is required to flow air through the duct. Therefore it is desirable that the turbulence must be created only in the region very close to the heat transferring surface, so that the power requirement may be lessened.This can be done by keeping the height of the roughness elements to be small in comparison with the duct dimensions. The key parameters that are used to characterize artificial roughness are :

1- Relative roughness pitch (p/e) : This is defined as the ratio of distance between two consecutive rib and height of the rib.
2- Relative roughness height ($e/D_h$) : The ratio of rib height to equivalent diameter of the air passage.
3- Angle of attack ($\alpha$) : Angle of attack is inclination of rib with direction of air flow in duct.
4- Shape of roughness element : The roughness elements can be two-dimensional ribs or three dimensional discrete elements, transverse or inclined ribs or V-shaped ( continuous or broken ribs with or without gap) . The roughness elements can also be arc-shaped wire or dimple or cavity or compound grooved. The most common shape of ribs is square but different shapes like circular, semi-circular and chamfered have also been considered to investigate thermo hydraulic performance.
5- Aspect ratio(W/H) : This is the ratio of duct width to duct height. This factor also plays a very crucial role investigating thermo - hydraulic performance.

## II. .Energy Balance And Efficiency Of Conventional Solar Air Heater

Energy balance of solar air heater is showing in fig. below -

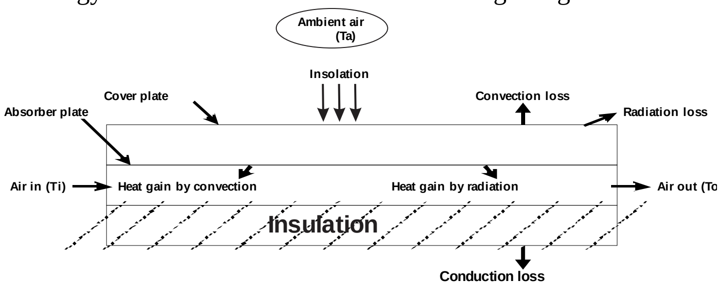


**Fig.1**

The energy balance equation can be written as follows

$Q_a = A_p [IR(\tau\alpha)_e] = Q_u + Q_1$ ............................................................................................................... [1]

Where $Q_a$ = energy absorbed by the absorber plate,

$A_p$ =the area of the absorber plate,

I = intensity of insolation,

R = conversion factor to convert radiation on horizontal surface to that on the absorber plane $(\tau\alpha)_e$ = effective Transmittance absorptance product of the glass cover-absorber plate combination, $Q_u$ = the useful energy gain and $Q_1$ is energy loss from the collector .

Collector efficiency factor (F') is expressed as :

$F' = 1 / (1 + U_1 / h_e)$

…………………………………………………………………………………………….…[2]

Where $h_e$ is the effective heat transfer coefficient between the absorber plate and flowing air.

The thermal efficiency of the collector is the ratio of useful heat gain to the incident solar energy falling on the collector therefore.

$\eta_{th} = Q_u / I A_P = F_R [(\tau\alpha)_e - U_1 (T_i - T_a) / I]$

…………………………………………………………………..….[3]

Various researchers have investigated the effect of different roughness parameters of artificial roughness elements in thermo-hydraulic characteristics for solar air heater. The most important effect produced by the presence of a rib on the thermo-hydraulic characteristics i.e. flow pattern is the formation of a vortex between ribs filling approximately two thirds of cavity and energy interchange with the main flow (karwa etal 1999). The vortices so generated are responsible for the turbulence which result in the desirable increase in heat transfer and the undesirable drop in pressure.

The experimental data includes thermocouple readings and air mass flow rates. This data have been reduced to obtain the average plate temperature, average air temperature, velocity of air flow in the ducts (Mass flow rate and flow Reynolds number) and the value of heat transfer coefficient. The thermo physical properties of the air have been taken at the average plate fluid temperature. Test results have been presented in the form of thermal parameters viz. Nusselt number, Reynolds number and also the thermal efficiency. Roughness's parameters have been given in the form of relative roughness height ($e/D_h$), relative roughness pitch (p/e) and angle of attack (α).

## III. Literature Review

**A.M.Lanjewar et al in paper [1]** ,heat transfer in rectangular duct using repeated ribs in W-continuous pattern had investigated .The W- pattern ribs have been tested for both pointing upstream and down - stream directions to the flow. The parameters used were Reynolds number range 2300-14000, relative roughness height (e/Dh)=0.03375, relative roughness pitch (p/e) 10, rib angle of attack $(\alpha) = 45^o$, thickness of plate 1mm, channel aspect ratio (W/H) 8, test length 1500 mm, hydraulic diameter 44.44 mm. It is found that the W-shaped ribs pointing downstream have better performance than W- shaped ribs pointing up stream to the flow.

**K.R.AHARWAR IN Paper[2]** has carried out an experimental investigation to study the heat transfer and friction characteristics by using discrete W- shaped roughness on one broad wall of solar air heater with an aspect ratio of 8:1. The parameters used were Reynolds number (Re) from 3000-15000, relative roughness height (e/Dh) in the range of 0.0168-0.338, relative roughness pitch (P/e) 10 and the angle of attack ( $\alpha$ ) in the range of $30^o$ - $75^o$ . The maximum enhancement of nusselt number and friction factor has been found to be 2.16 and 2.75 times that of smooth duct for an angle of attack of $60^o$.

**ARVIND KUMAR IN PAPER [3]** , had carried out an experimental study of heat transfer and friction faction factor data rib geometry **.** Experiment based on the range of relative roughness height (e/D) of 0.015-0.033, Reynolds number (Re) range of 3000-18000 and relative roughness pitch (p/e) of 12.12 to 60.17 and wedge angle was $8\text{-}15^0$. It has been observed that the maximum heat transfer occurs for a relative roughness pitch of about 7.57 . The maximum enhancement of heat transfer at wedge angle was about $10^0$. and also enhancement in Nusselt number up to 2.4 times while the friction factor increases up to 5.3 times as compared to smooth duct.

**Saini and Saini in paper[4]** had investigated solar air heater having artificial roughness in the form of arc-shape parallel wire. The effect of system parameters such as relative roughness height (e/d) and arc angle (a/90) have been studied on Nusselt number (Nu) and friction factor (f) with Reynolds number (Re) varied from 2000 to 17000. the maximum enhancement in Nusselt number has been obtained as 3.80 times corresponding the relative arc angle (a/90) of 0.3333 at relative roughness height of 0.0422. However, the increment in friction factor corresponding to these parameters has been observed 1.75 times only.

**Saini and Verma in paper[5]** had used dimple-shape artificial roughness on the underside of the absorber plate in**.** The maximum value of Nusselt number has been found corresponds to relative roughness height (e/D) of 0.0379 and relative pitch (p/e) of 10. While minimum value of friction factor has been found correspond to relative roughness height (e/D) of 0.0289 and relative pitch (p/e) of 10.

**Karwa in paper[6]** had experimentally investigated the effect of repeated rectangular cross-section ribs on heat transfer and friction factor for duct aspect ratio (W/H) range of 7.19-7.75, relative roughness pitch (p/e) value of 10, relative roughness height (e/D) range of 0.0467-0.050, Reynolds number (Re) range of 2800-15,000 as shown in Fig. It was explained that vortices originating from the roughness elements beyond the laminar sub-layer were responsible for heat removal as well as increase in friction factor. The friction factor was found to be 2.68-2.94 times over smooth duct.

**Gupta in paper[7]** had investigated the effect of relative roughness height, angle of attack and Reynolds number on heat transfer and friction factor in rectangular duct having circular wire ribs on the absorber plate. It was found that the heat transfer coefficient in roughened duct could be improved by a factor up to 1.8 and the friction factor had been found to increase by a factor up to 2.7 times of smooth duct. The maximum heat transfer coefficient and friction factor were found at an angle of attack of $60^0$ and $70^0$ respectively in the range of parameters investigated. The thermo-hydraulic performance of roughened surfaces had been found best corresponding relative roughness height e/D of 0.033 and the Reynolds number corresponding to the best thermo-hydraulic performance were around 14,000 in the range of parameters investigated.

**Momin et al in paper[8]** had experimentally investigated the effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics in rectangular duct of solar air heater . The investigation covered Reynold number range of 2500-18000 , relative roughness height of 0.02-0.034 .In addition , CFD based fluid flow and heat transfer analysis is also carried out **in paper [13-15]** by various researchers .

## IV. Correlations Developed Between Heat Transfer And Friction Factor For Different Roughness Geometries

Correlations between heat transfer performance and friction factor is presented in a tabular form as follows :-

| Types of ribs and Authors | Parameters | Correlations | |
|---|---|---|---|
| | | Heat transfer | Friction factor |
| [1]W-shaped ribs, Atul Lanjewar et al. | Re: 2300-14000<br>p/e: 10<br>$e/D_h$: 0.018-0.03375<br>W/H : 8.0 α: 300-700 | $Nur = 0.0613 \times (Re)^{0.9079} \times (e/D_h)^{0.4487} \times (\alpha/60^0)^{-0.1331} \times [\exp(-0.5307(\ln (\alpha/60^0))^2]$ | $fs = 0.6182(Re)^{-0.2254} (e/D_h)^{0.4622} (\alpha/60^0)^{0.0817} \times [\exp(-0.28(\ln(\alpha/60^0))^2)]$ |
| [2]Inclined rib with gap, K.R. Aharwal et al. | Re: 3000–18000,<br>e/Dh: 0.0377<br>g/e: 0.5–2, d/W: 0.1667–0.667, W/H: 5.84, $\alpha : 60^0$ | $Nu = 0.002Re^{1.08}(p/e)^{1.87} \times \exp[0.45(\ln(p/e))^2] (\alpha/60)^{0.006} \times \exp[-0.65(\ln \alpha/60)^2] (d/W)^{-0.32} \times \exp[-0.12(\ln d/W)^2](g/e)^{-0.03} \times \exp[-0.18(\ln g/e)^2](e/D_h)^{0.5}$ | $f = 0.071Re^{-0.133} (p/e)^{1.83}\exp[-0.44(\ln (p/e))^2] \times (d/W)^{-0.43} \times \exp[-0.14(\ln d/W)^2] (g/e)^{-0.052} \times (\alpha/60)^{0.67} (\exp[0.12(\ln g/e)^2] (e/D_h)^{0.69}$ |
| [3]Discrete W-shaped ribs,<br>Arvind Kumar et al. | Re: 3000-15000 p/e : 10<br>e/Dh: 0.0168–0.0338<br>α: 300-750 | $Nur = 0.105 \times (Re)0.873 \times (e/D_h)^{0.453} \times (\alpha/60^0)^{-0.081} \times \exp[-0.59 \times (\ln(\alpha/60^0)^2)]$ | $fr = 5.68 \times (Re)^{-0.40} \times (e/D_h)0.59 \times (\alpha/60^0)^{-0.081} \times \exp[-0.579 \times (\ln (\alpha/60^0))^2]$ |

| | | | |
|---|---|---|---|
| [4]Arc shaped ribs, Saini and Saini | Re: 2000–17,000(p/e): 10(e/d): 0.021–0.042a/90: 0.33–0.66 | Nu = $0.001047\times Re^{1.3186}\times (e/D_h)^{0.3772}\times(\alpha/90^0)^{-0.1198}$ | f = $0.14408\times Re^{-0.17103}\times (e/D_h)^{0.1765}\times(\alpha/90^0)^{0.1185}$ |
| [5]Dimpled shaped rib Saini and Verma | Re: 2000–12,000 (p/e): 8–12 (e/d): 0.018–0.037 | Nu = $5.2\times10^{-4}Re^{1.27}\times(p/e)^{3.15}\times$ [exp(-2.12)(log((p/e)))2] $(e/D_h)^{0.033}\times$ $[\exp(-3)(\log((e/d))^2]$ | f = $0.642\times Re^{-0.423}\times(p/e)^{-0.465}\times$ $[\exp(0.054)(\log((p/e)))^2]\times$ $(e/D_h)^{-0.0214}[\exp(0.84)(\log((e/d))^2]$ |
| [6]Chamfered rib Karwa et al. | Re: 3000–20,000 (p/e): 4.5, 5.8, 7 and 8.5 (e/d): 0.0141–0.0328 W/H: 4.8, 6.1, 7.8, 9.66 and 12 f = _15, 0, 5, 10, 15 and 18 | G =103.77 $e^{-0.006}(W/H)^{0.5}(p/e)^{2.56}$ exp[0.7343{ln $(p/e)\}^2](e+)^{-0.31}$<br>For 7 ≤e+< 20<br>G =$32.26e^{-0.006}(W/H)^{0.5}(p/e)^{2.56}$ exp[0.7343{ln $(p/e)\}^2](e+)^{0.08}$<br>For 20 ≤ e+ ≤60 | R=$1.66e^{-0.0078}(W/H)^{-0.4}(p/e)^{2.695}$ exp[-0.762{ln (p/e)}2]$(e+)^{-0.075}$]<br>For 7 ≤e+< 20,<br>R =$1.325e^{-0.0078}(W/H)^{-0.4}(p/e)^{2.695}$ exp[-0.762{ln $(p/e)\}^2$] For 20 ≤ e+≤ 60 |
| [7]Inclined continuous ribs,<br>Gupta et al. | Re: 3000-18000,<br>p/e: 7.5 and 10,<br>e/Dh: 0.020-0.05,<br>α: $30^0$-$90^0$ | Nu = $0.00247(e/Dh)^{0.001}(W/H)^{-0.06}Re^{1.084}$ $[\exp\{-0.04(1-\alpha/60^0)^2\}]$,for $e^+ < 35$,<br>Nu = $0.0071(e/Dh)^{-0.24}(W/H)^{-0.028}Re^{0.88}$ $[\exp\{-0.475(1-\alpha/60^0)^2\}]$, for $e^+ \geq 35$ | f = $0.1911(e/Dh)^{0.195}(W/H)^{-0.093}Re^{-0.165}$ $[\exp\{-0.0993(1-\alpha/70^0)^2\}]$ |
| [8]V-shaped ribs,<br>Momin et al. | Re: 2500-18000, p/e: 10-40, e/Dh: 0.01-0.03, | Nu = $0.067Re^{0.888}(e/D_h)^{0.424}(\alpha/60^0)^{-0.077}$ $[\exp\{-0.782(\ln(\alpha/60^0))^2\}]$ | f = $6.266\ Re^{-0.425}(e/D_h)^{0.565}(\alpha/60^0)^{-0.093}$ $\exp[-0.719(\ln(\alpha/60^0))^2]$ |
| [9]Transverse broken rib,<br>M.M.Sahu et al. | Re: 3000-12000, p: 10-30, e: 1.5, e/Dh: 0.0338, α: $90^0$ | | |

## V. Conclusions

This paper reviews the investigation carried out by various investigators in order to enhance the heat transfer by use of artificial roughness . Use of artificial roughened surfaces with different type of roughness geometries of different shapes sizes and orientation is found to be the most effective technique to enhance the heat transfer rate with little penalty of friction . Roughness in the form of ribs and wire matrix were mainly suggested by different investigators to achieve better thermal performance. Among all rib roughness was found the best performer as for as thermal performance is concerned . Correlations developed for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries for different investigators are also shown in tabular form. These correlations can be used to predict the thermal efficiency, effective efficiency and then hydraulic performance of artificial roughened solar air heater ducts. Information provided in the present paper may be useful to the beginners in this area of research to find out and optimize the new element geometries for the maximum enhancement of heat transfer.

## VI. Nomenclatures

| | |
|---|---|
| A | Surface area of absorber plate, $m^2$ |
| B | half-length of full V-rib element, m |
| Cp | specific heat of air, J/kg K |
| Dh | equivalent or hydraulic diameter of duct, m |
| e | rib height, m |
| g | groove position, m |
| h | Heat transfer coefficient, $w/m^2k$ |
| H | depth of air duct, m |
| I | intensity of solar radiation, $w/m^2$ |
| K | thermal conductivity of air, w/mk |
| L | length of test section of duct or long way length of mesh, m |
| m | mass flow rate, kg/s |
| p | pitch, m |
| Dp | pressure drop, pa |
| qu | useful heat flux, $w/m^2$ |
| Qu | useful heat gain, w |
| $Q_1$ | heat loss from collector, w |
| $Q_t$ | heat loss from top of collector, w |

| | |
|---|---|
| S | length of discrete rib or short way length of mesh, m |
| $T_o$ | Fluid outlet temperature, $o_K$ |
| $T_i$ | fluid inlet temperature, $o_K$ |
| $T_a$ | ambient temperature, $o_K$ |
| Tpm | mean plate temperature, $o_K$ |
| W | width of duct, m |

**Dimensionless parameters**

| | |
|---|---|
| e/Dh | relative roughness height |
| e/H | rib to channel height ratio |
| f | friction factor |
| g/p | relative groove position |
| Nu | Nusselt number |
| Nus | Nusselt number for smooth channel |
| Nur | Nusselt number for rough channel |
| p/e | relative roughness |
| Re | Reynolds number |
| St | Stanton number |
| W/H | duct aspect ratio |

**Greek Symbols**

| | |
|---|---|
| $\alpha$ | rib angle of attack |
| $\eta_{th}$ | thermal efficiency |
| $\mu$ | dynamic viscosity ns/m$^2$ |
| $\rho$ | density of air kg/m$^3$ |

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